Co-Optimization of
Fuels & Engines

Project ID: FT057

Co-Optimization of Fuels and Engines (Co-Optima): Emissions, Emission Control, and Sprays

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John Storey, Melanie DeBusk, Josh Pihl,
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June 8, 2017

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Co-Optima DOE VTO Management Team:
Kevin Stork, Mike Weismiller, Leo Breton, & Gurpreet Singh

Overview

Timeline

- Project start date: 10/1/2015
- Project end date:* 9/30/2018
- Percent complete: 56%

Budget

Advanced Engine Development	FY16 ($K)	FY17 ($K)	FY18 ($K)
ORNL (E.1.3.1): Fuel Impacts on Emissions Control Performance & Durability	341	175	350
ORNL (E.1.3.2): Fuel Impact on GDI PM Formation and Gaseous Emissions During Cold Start	183	188	188
ORNL (E.1.3.3): Fuel Contribution to PM From Kinetically-Controlled Combustion	183	188	188
NREL (E.1.3.4): Fuel Effects on Emissions and Aftertreatment	244	250	250
ANL (E.1.4.1): Studies of Sprays and Mixture Formation	200	200	200
SNL (E.1.4.2): Complete Installation of High-Throughput Spray Facility	1150	1050	212

Barriers

- **Complexity**: Introduction of new fuels and vehicles involves large number of stake holders with competing value propositions
- **Timing:** schedule for completing R&D and achieving market impact is extremely ambitious

Partners

- Partners include a total of:
  - 9 national laboratories
  - 13 universities
  - External advisory board
  - Stakeholders

*Start and end dates refer to three-year life cycle of DOE lab-call projects, Co-Optima is expected to extend past the end of FY18

Overview of Projects

Fuels can have a pronounced impact on spray structure, mixture formation, emissions, and emissions control systems for all SI and ACI engine technologies. Projects addressing these areas (FY17 budget):

- **SNL: High-throughput spray chamber ($1150K)**
  - Lyle Pickett
- **ANL: X-ray imaging of GDI sprays with alcohol blends ($200K)**
  - Christopher Powell
- **NREL: Particulate Matter Index (PMI) refinement ($250K)**
  - Bob McCormick and Matt Ratcliff
- **ORNL: PM formation and oxidation fundamentals ($376K)**
  - Fuel Impact on GDI PM Formation & Gaseous Emissions During Cold Start
  - Fuel Contribution to PM From Kinetically-Controlled Combustion
  - John Storey and Melanie DeBusk
- **ORNL: Fuel Impacts on Emissions Control Performance & Durability ($175K)**
  - Todd Toops and Josh Pihl

Milestones

Milestone	Date
SNL: Design and place contracts for high-throughput chamber components **{COMPLETE}**	9/30/2016
NREL: Complete GDI (SCE) PM emissions test matrix with objective of improving predictions of PMI **{COMPLETE}**	9/30/2016
ORNL: Evaluate dual SCR system with ethanol-based fuels to determine parameters that enable the emissions targets **{COMPLETE}**	9/30/2016
ORNL: Measure catalytic light-off behavior of at least five SI-HPF candidates (encompassing five different functional groups) over a three-way catalyst. **{DELAYED due budget reduction, \$350k → \$175k)**	3/31/2017 ↓ 9/30/2017
SNL: Install completed lower pressure vessel with high-power (60 kW) heater controls	9/30/2017

Spray Projects

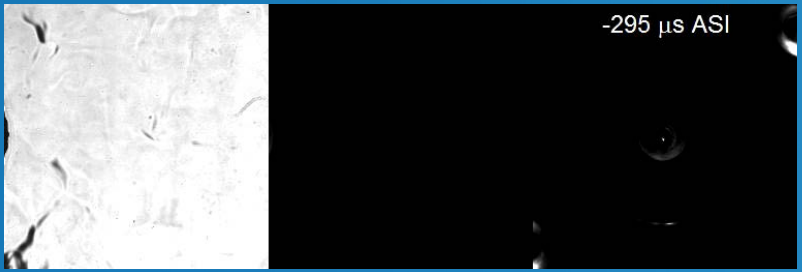
Project Summary #1

Sandia National Laboratories

High-throughput spray chamber ($1050K)

Lyle Pickett (PI)

Liquid and vapor spray measurements of gasoline multi-hole injector

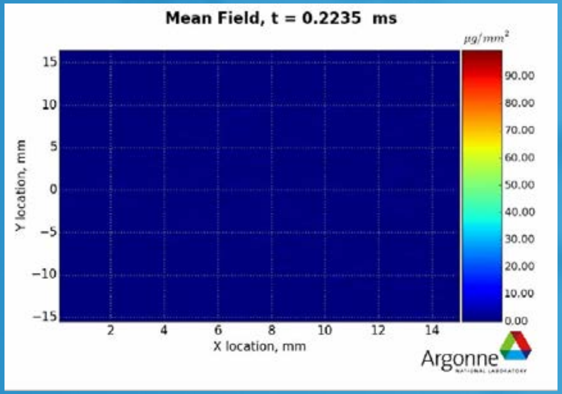


Project Summary #2

Argonne National Laboratory

X-ray Studies of Sprays and Mixture Formation ($200K)

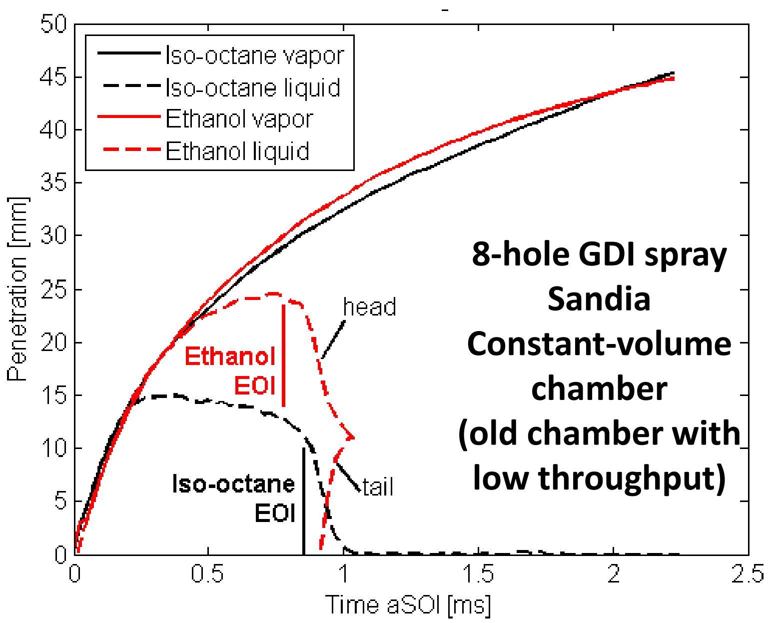
Christopher Powell (PI)
Daniel Duke, Alan Kastengren, Katarzyna Matusik



Relevance: Fuels affect sprays, and sprays affect efficiency

Objectives and Relevance

- Improve understanding of how fuel properties impact mixture formation
  - Fuel distribution affects ignition, burn-rate, COV, particulate matter, temperature field, knock sites in an engine
- Test the Central Fuels Hypothesis:
  - quantify ways that the physical properties of the fuel affect the fuel distribution and the initial conditions of combustion
- Deliver data for validation of spray simulations



Approach

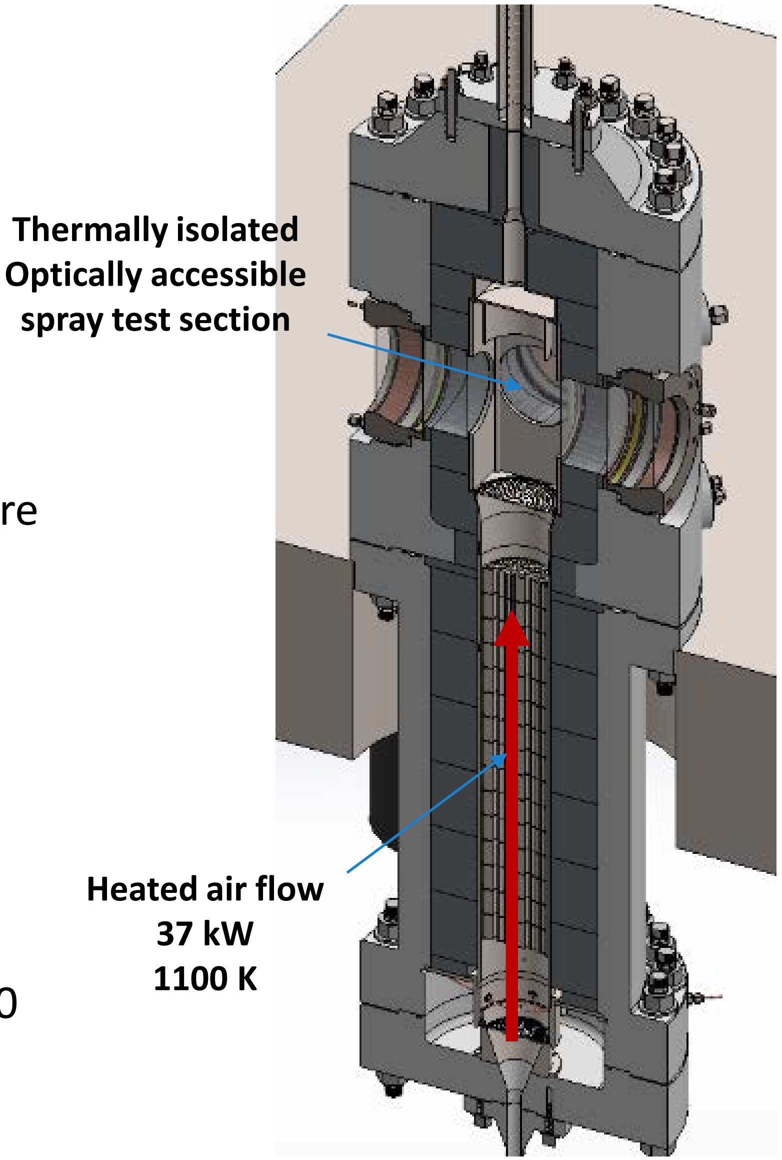
- Coordinate spray research efforts at SNL and ANL using the same injector hardware and operating conditions
- **SNL**: Develop and implement a continuous flow spray chamber that reproduces engine T & P and enables a 300X data throughput improvement
  - Large-volume, uniform-temperature (unlike engines or IQT-like chambers)
- **ANL**: Using X-ray technique at the Advanced Photon Source (APS) perform detailed measurements of GDI-based fuel injection sprays

Approach/Accomplishments

Status of chamber installation:

- Facility installations in progress:
  - Compressed air and nitrogen to 150 bar
  - Vacuum operation to mimic flash boiling conditions
  - Water cooling system for vessel and exhaust
- Operator room construction:
  - Safety barricade to guard against window failure
  - Heater PID control with intrinsically safe feedback for air flow and cooling flow
- Optical access:
  - Support table with cutouts for chamber anchored to floor for seismic restraint
- Fuel system:
  - Small-volume (50 mL) syringe pump up to 2000 bar for work with small test samples

Spray Chamber



Approach/Accomplishments

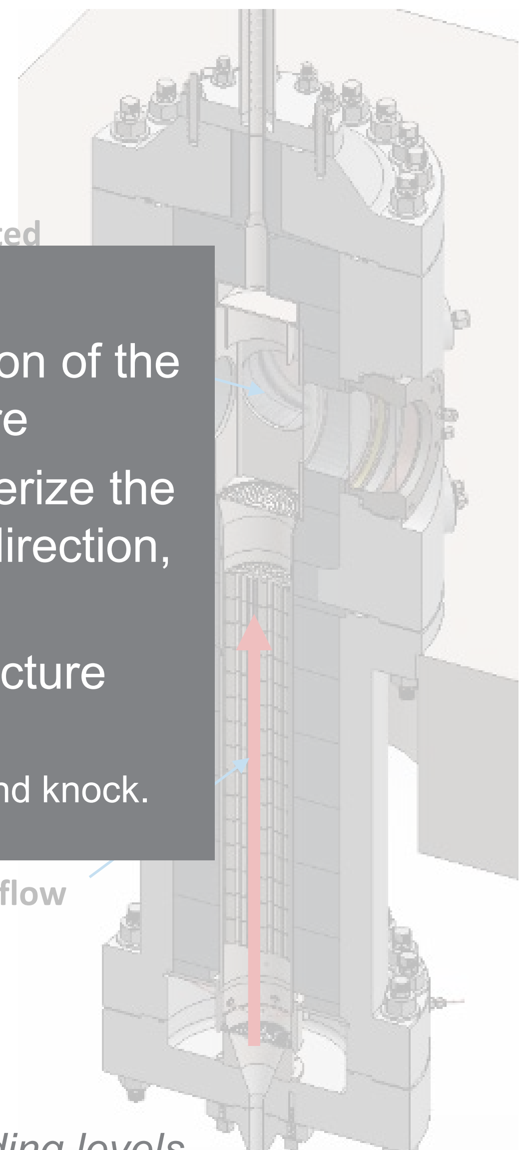
Status of chamber installation:

- Facility installations in progress:
  - Compressed air and nitrogen to 150 bar
  - Vacuum operation to mimic flash boiling conditio
  - Water c
- Operator
  - Safety b
  - Heater F feedbac
- Optical ac
  - Support anchored to floor for seismic restraint
- Fuel system:
  - Small-volume (50 mL) syringe pump up to 2000 bar for work with small test samples

Future Work/directions

- Characterize the gas temperature distribution of the spray chamber and fuel injector temperature
- For the leading-candidate SI-fuels, characterize the vapor envelope, liquid penetration, plume direction, and droplet size
- Characterize the end-of-injection liquid structure and film formation for all SI-intended fuels
  - expected to contribute to particulate formation and knock.

Spray Chamber



Any proposed future work is subject to change based on funding levels

New High Pressure Fuel System for **Flammable** Fuels

Progress

- Previous x-ray measurements were limited to combustible, not flammable fuels
  - e.g. diesel, gasoline calibration fluids
- New high pressure fuel system has been procured
  - Suitable for a broad range of fuels at pressure up to 350 bar
- Controls and safety features are currently being implemented

Deliverables

- Spray breakup will be linked with the physical properties of the fuel
- Fuel impact on mixture formation will be quantified
- Dataset linking fuel properties to mixture formation will be delivered to the modeling community, allowing development and validation of improved spray, combustion, and engine models

New High Pressure Fuel System for **Flammable** Fuels

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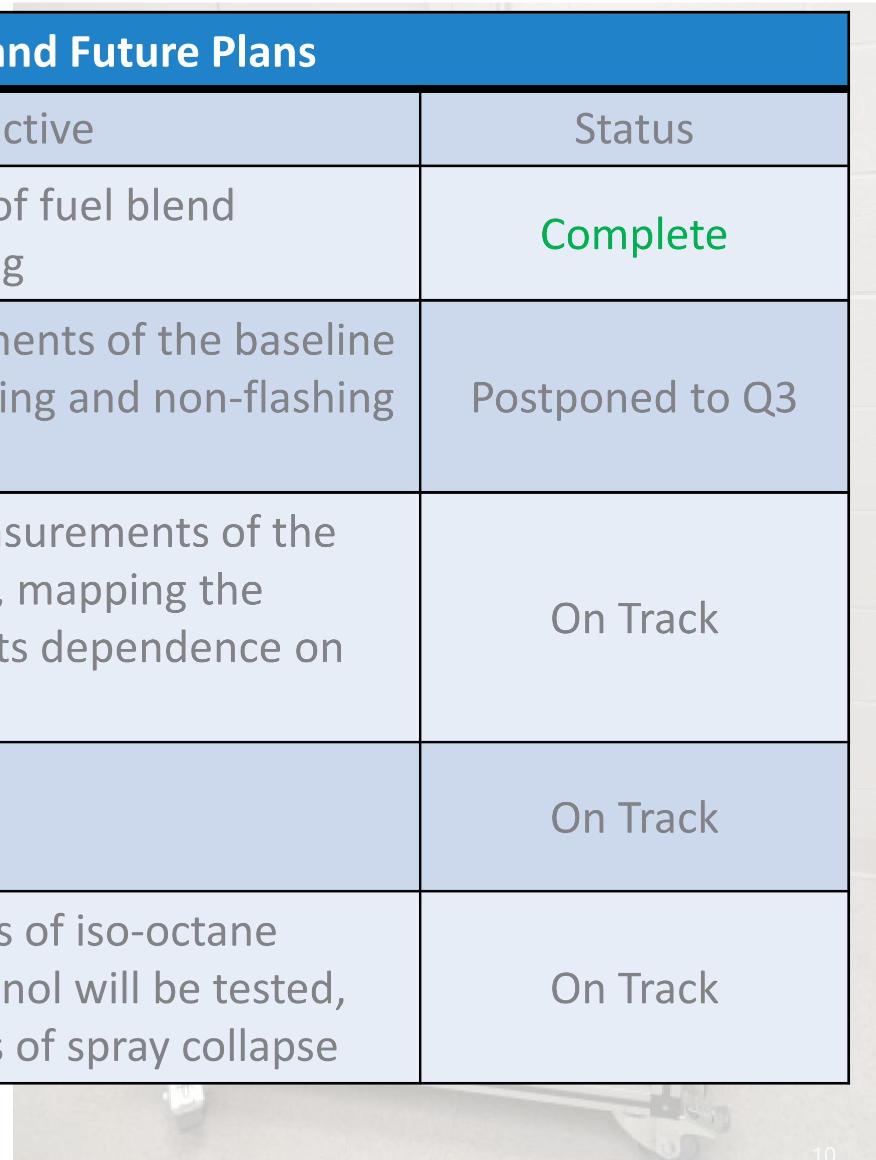


Project Schedule and Future Plans		
Date	Objective	Status
December 2016	Select a priority list of fuel blend candidates for testing	Complete
March 2017	Complete measurements of the baseline fuel under flash-boiling and non-flashing conditions	Postponed to Q3
June 2017	Complete spray measurements of the selected fuel blends, mapping the fuel/air mixing and its dependence on fuel properties.	On Track
September 2017	Report results	On Track
FY2018	Spray measurements of iso-octane blends with iso-butanol will be tested, studying the triggers of spray collapse	On Track

development and validation of improved spray, combustion, and engine models

Any proposed future work is subject to change based on funding levels

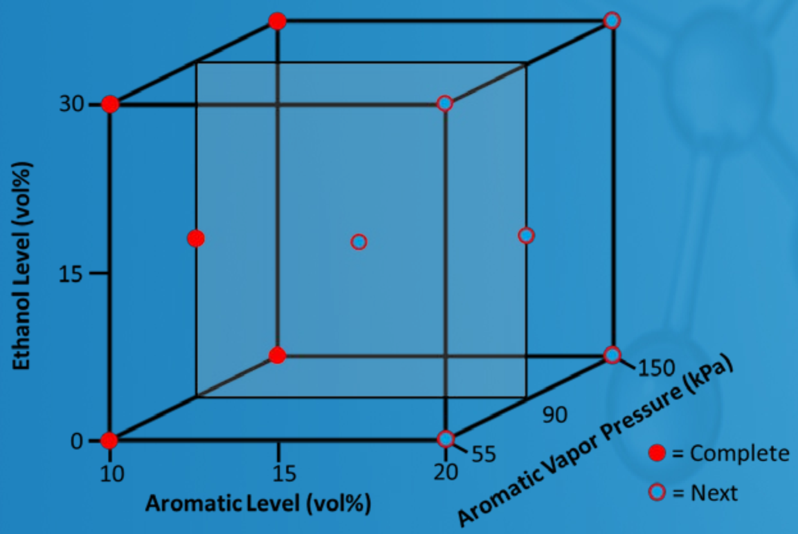
Project Summary #3

National Renewable Energy Laboratory

Fuel Effects on Emissions and Aftertreatment ($250K)

Bob McCormick and Matt Ratcliff (co-PIs)

Jonathan Burton



Fine Particle Emissions: Particulate Matter Index (PMI)

Relevance

- PMI was developed for predominantly hydrocarbon fuels
- Provides a fuel ranking for PM emissions in a given vehicle
- High PMI fuels may require gasoline particle filter
- GPF has a fuel economy impact – backpressure and regeneration
- Honda reported global average PMI to be about 1.6
- The merit function score penalizes engine efficiency by 0.7% if PMI is greater than 1.6
- Increasing penalty if PMI is higher

Based on detailed hydrocarbon analysis of the base fuel and the quantity of added oxygenate

Tendency to form soot

$$PMI = \sum_{i=1}^{n} \left[\frac{(DBE_i + 1)}{VP(443K)_i} \times Wt_i \right]$$

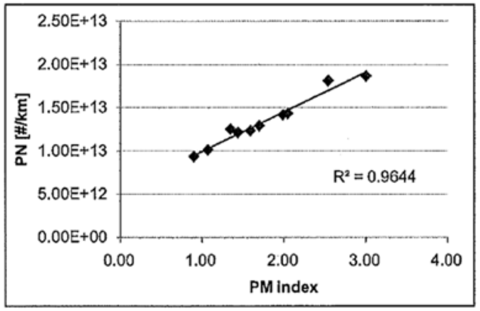
Driver to evaporate and mix with air

Where-

$DBE = (2C + 2 - H)/2$

Wt_i = *Weight fraction of compound*

VP = *Vapor pressure at 443K (170ºC)*



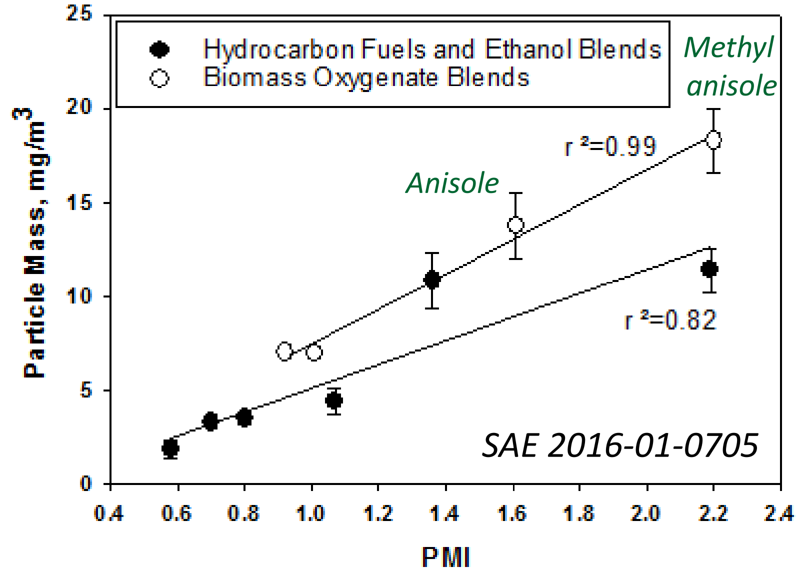
GDI engine equipped cars, FTP-75 bag 1

Aikawa, K., Sakurai, T., Jetter, J. J.
SAE 2010-01-2115

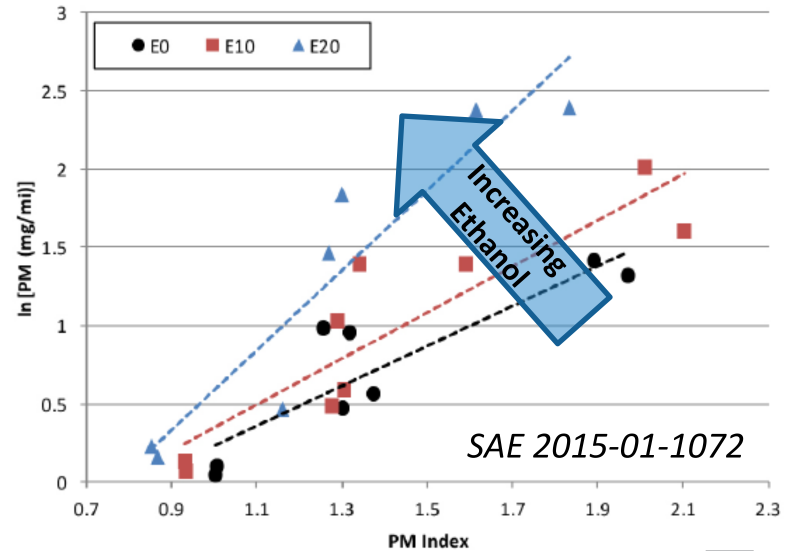
$$
\begin{aligned}
Merit = {} & \frac{(RON_{mix} - 91)}{1.6} - K\frac{(S_{mix} - 8)}{1.6} \\
& + \frac{0.085[ON/kJ/kg_{mix}]\cdot((HoV_{fuel}/(AFR_{stoich}+1)) - (415[kJ/kg_{fuel}]/(14.3[-]+1)))}{1.6} \\
& + \frac{((HoV_{fuel}/(AFR_{stoich}+1)) - (415[kJ/kg_{fuel}]/(14.3[-]+1)))}{15.38} \\
& + \frac{(S_{L\,mix} - 46[cm/s])}{5.4} \\
& - H(PMI - 1.6)[0.7 + 0.5(PMI - 1.4)] \\
& + 0.008\,^{\circ}C^{-1}(T_{c,90,conv} - T_{c,90,mix})
\end{aligned}
$$

Does PMI Breakdown for Oxygenates?

- Studies of soot formation tendency and soot precursor formation suggest that it will
  - Anisole forms cyclopentadienyl radical which couples to naphthalene (*J. Phys. Chem. A* 2010, <u>114</u>, 9043–9056)
  - Secondary alcohol dehydration to alkene (*Environ Sci Technol*, 2011, <u>45</u> (6), pp 2498–2503)

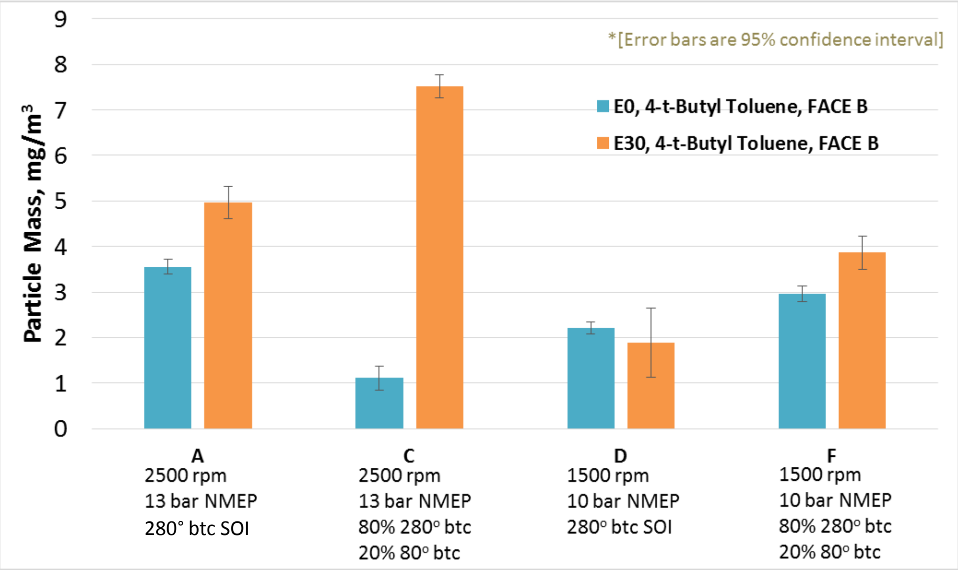


- High heat of vaporization (from ethanol) may lower effective vapor pressure of high boiling aromatics, increasing PM emissions



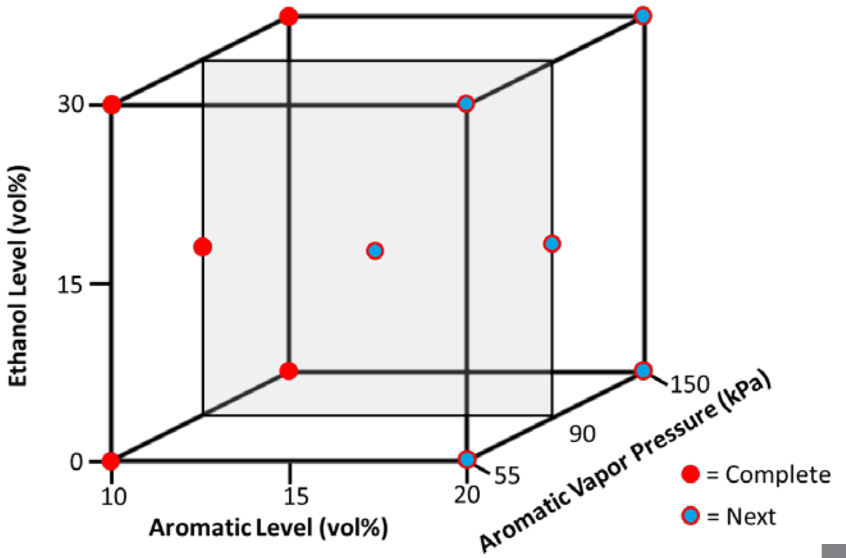
Demonstrated that under some conditions increased heat of vaporization can cause heavy aromatics to form more PM

Approach and Technical Accomplishments/Progress



- Factorial experimental design to quantify competing effects of
  - dilution (reduces PM)
  - evaporative cooling (increases PM)
- Dilution effects dominating for more highly volatile aromatics than tert-butyltoluene at 10 vol%

- GDI single cylinder engine
- PM mass by AVL Microsoot sensor, dilute, denuded exhaust
- Compares E0 and E30 blends at constant t-butyltoluene vol%



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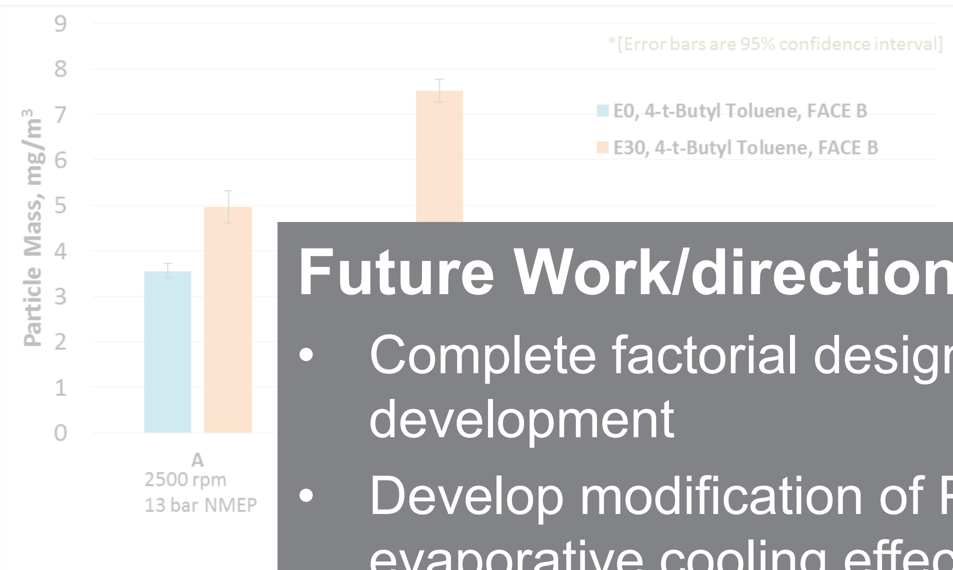
Approach and Technical Accomplishments/Progress



- Factorial experimental design to quantify competing effects of
  - dilution (reduces PM)
  - evaporative cooling (increases PM)

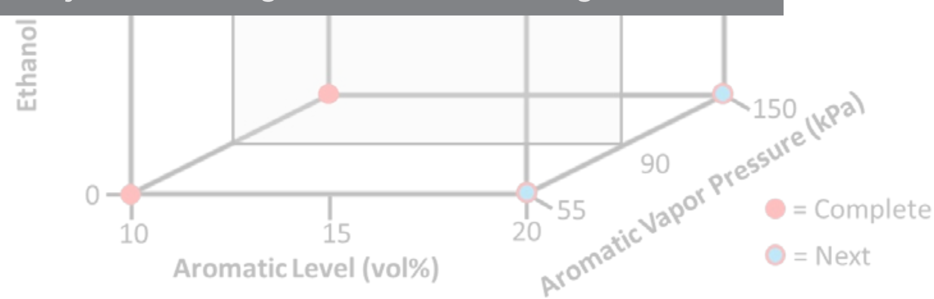
… for more … an tert-

- GDI sing…
- PM mas… sensor, … exhaust
- Compares E0 and E30 blends at constant t-butyltoluene vol%

Future Work/directions

- Complete factorial design and regression model development
- Develop modification of PMI to accommodate evaporative cooling effects and oxygenate chemistry
- Examination of injection strategies and parameters to leverage fuel properties to avoid PM emissions

Any proposed future work is subject to change based on funding levels



Project Summary #4

Oak Ridge National Laboratory

PM formation and oxidation fundamentals ($376K)

1.3.2 Fuel Impact on GDI PM Formation and Gaseous Emissions During Cold Start

1.3.3 Fuel Contribution to PM From Kinetically-Controlled Combustion

John Storey and Melanie DeBusk (co-PIs)

Relevance

Overall Objective

- Emission regulations dictate use of aftertreatment hardware
  - GPF may be required to meet 2025 PM Regulations (1 mg/mile)
  - GPF causes backpressure – reducing engine efficiency, increasing LSPI potential
- Study how PM is affected by advanced fuel properties and bio-blend fuels being considered to improve overall efficiency
  - Increased oxygenate content (i.e. oxygenated bio-blends)
  - Chemical properties of bio-blend (functional groups and level of saturation)
- Evaluate merit function PM control term to predict fuel sooting

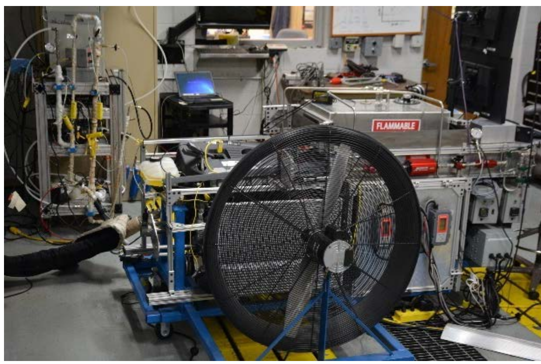
FY17 Objective

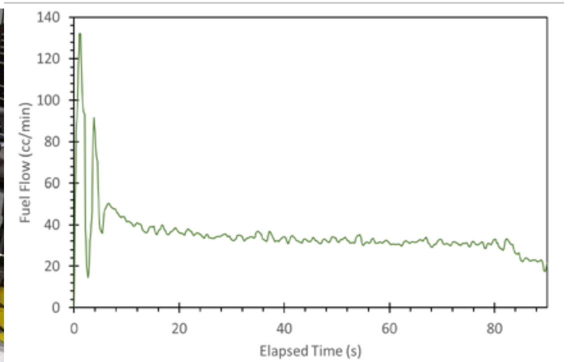
- Cold-Start major contributor to PM mass during FTP drive cycle
- Isolate initial cold-start PM production as function of fuel properties
  - How does oxygenated fuel follow PMI based PM predictions?
  - Does Cold-Start PM follow PMI index?
  - Does PMI control term in Merit Function capture this trend?
  - Statistical confidence in results

Approach

A 2.0 L start-cart with forced cooling allowed 12-16 cold-starts per day was used to collect PM from during a Cold-Start Transient (90s). Dry-Soot and PM production sampled to study fuel sooting levels for multiple fuel blends to evaluate how different oxygenated fuel blends impact PM during high sooting engine operation.

Cold-start fueling strategy using Start-Cart





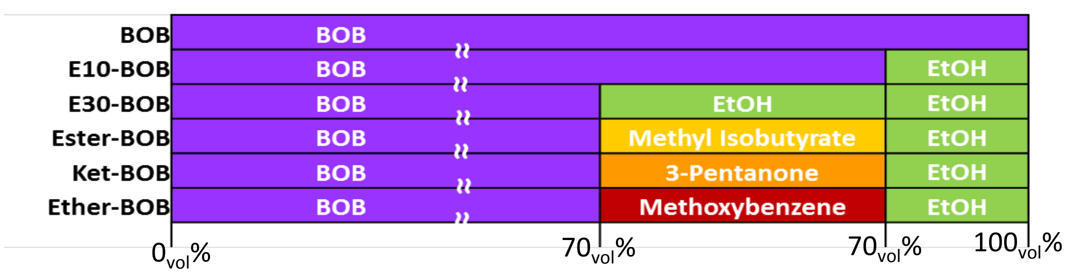
- Coolant in/out, Engine Head and Block and oil sump (16-19°C)
- CO_2 measurements from all fuels studied within 1% (bag sampling)

Oxygenated Fuel Blends Studied:

Splash blending with BOB used to make Co-Optima E30

*E0-c : Tier II E0 Lube Certification fuel

*E10-c: Tier III E10 Certification fuel



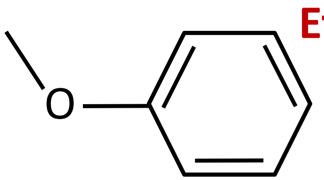
Statistical Confidence in Results

- On-line measurement
  - 18 cold-starts transients per fuel
  - AVL Micro Soot Sensor measurements
- Gravimetric Mass Sampling
  - Triplicate filter samples per fuel
  - 6 cold-starts per filter

Approach

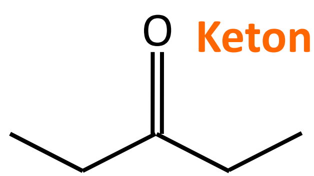
A 2.0 L start-cart with forced cooling allowed 12-16 cold-starts per day was used to collect PM from during a Cold-Start Transient (90s). Dry-Soot and PM production sampled to study fuel sooting levels for multiple fuel blends to evaluate how different oxygenated fuel blends impact PM during high sooting engine operation.

Ether



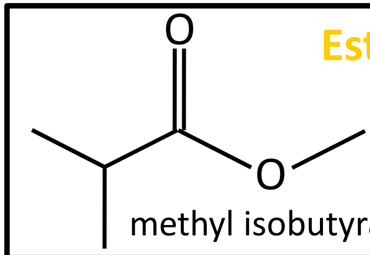
methoxy benzene (anisole)

Ketone



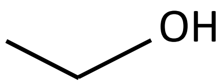
3-pentanone

Ester



methyl isobutyrate

Alcohol



ethanol

Does chemical functionality of oxygenated bio-fuel impact PM?

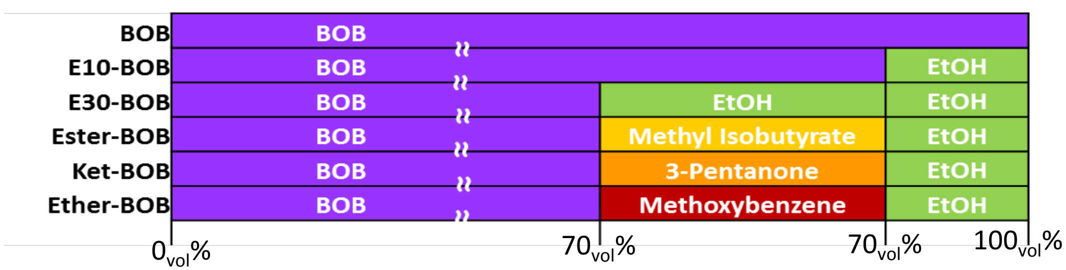
- Mass, Number, Size and/or Chemistry

Oxygenated Fuel Blends Studied:

Splash blending with BOB used to make Co-Optima E30

*E0-c : Tier II E0 Lube Certification fuel

*E10-c: Tier III E10 Certification fuel



Statistical Confidence in Results

- On-line measurement
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- Gravimetric Mass Sampling
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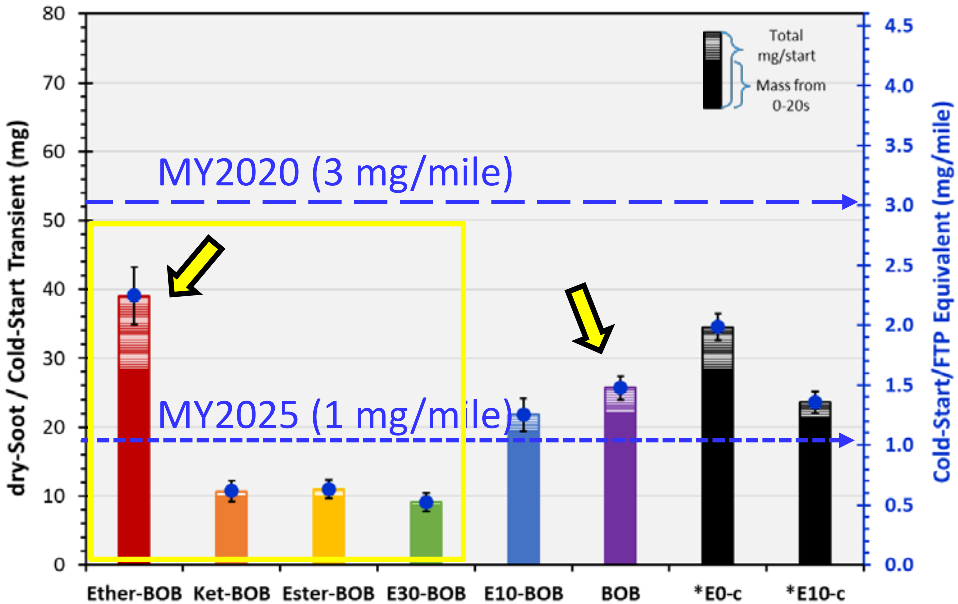
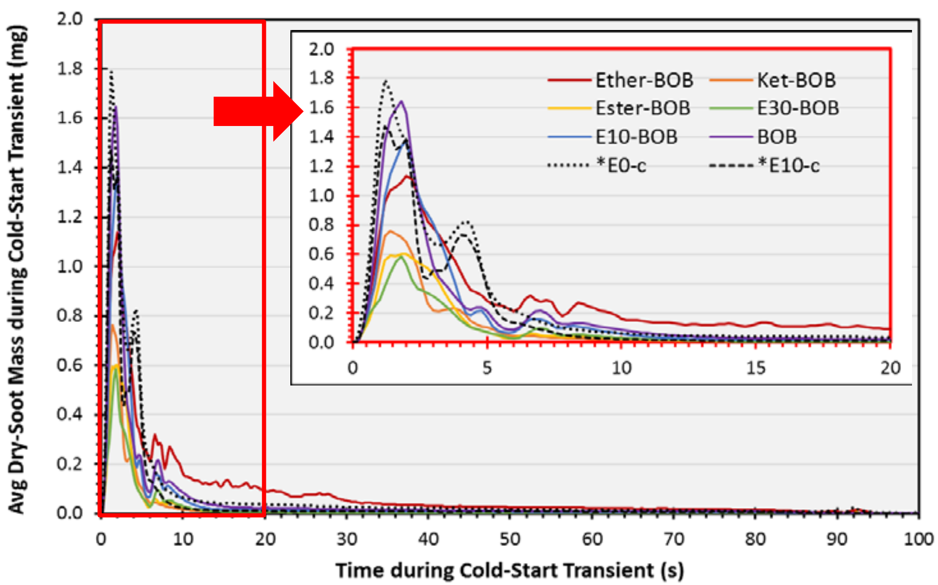
ORNL: *PM formation and oxidation fundamentals*

Oxygenated Fuel Blends Impact on dry-Soot Mass

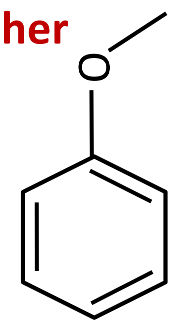
On-line measurement (AVL Microsoot Sensor)





- 30_{vol}% Oxygenate Fuels
  - Typically showed a significant reduction in dry-soot
  - **Ether-BOB** (anisole)
    - More soot than **BOB**
    - ~4x the mass of other 30% oxygenated fuels

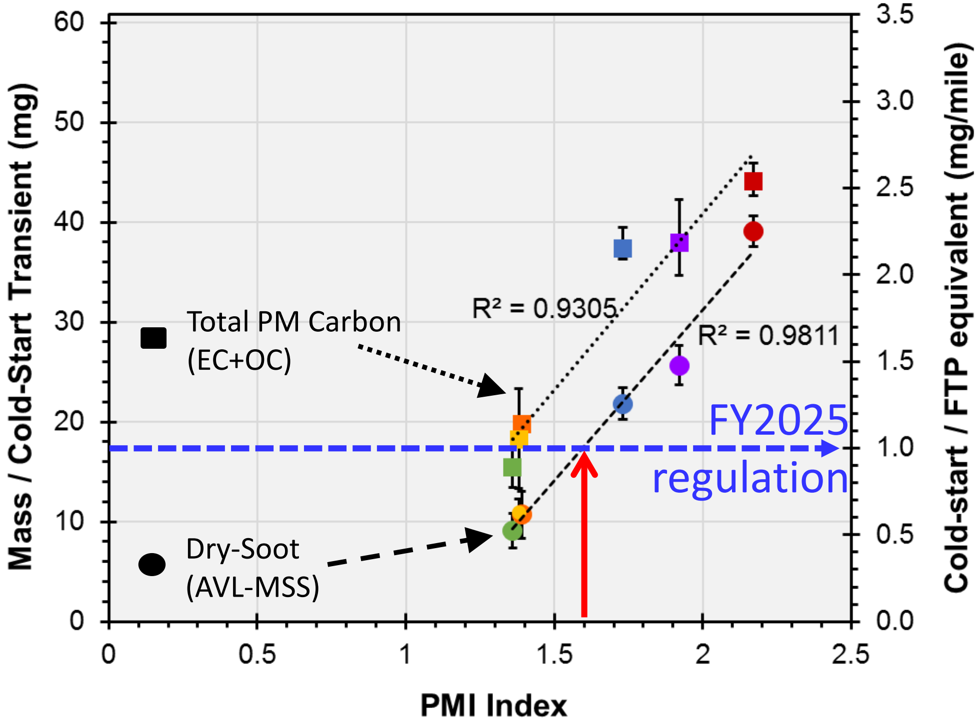
Ether



methoxy benzene

  - contains 20_{vol}% methoxybenzene an oxygenated aromatic
  - Impact of functional group or double bonds?
- First 20s of cold-start transient
  - Soot production profile varies by fuel
  - Most of soot produced (by mass)

Cold-Start Sooting Trend Predicted by PMI



Ether - BOB
Ketone – BOB
Ether –BOB
E30 – BOB
E10 – BOB
BOB

Merit Function
PM Control Term

$$-H(PMI - 1.6) \times [0.7 + 0.5(PMI - 1.4)]$$

- Mass quantity of PM will dictate need for a particulate filter (PF)
- Merit Function's PM Control Term uses PMI to predict need for PF
    - In cylinder control and use of a PF can cause a decrease in efficiency
- Cold-start dry-soot data supports update of -H(X) function
    - From 2.0 to 1.6
- Total PM carbon (EC +OC) shows greater PM mass but trend follows PMI

Cold-Start Sooting Trend Predicted by PMI

Future Work/directions

- Study oxygenate influence on GDI cold-start PM chemistry
  - Gravimetrically sampled PM
  - On-line measurements (TSI-EEPS)
- Study potential pathways to ACI PM organic carbon and its formation
  - Organic carbon is the main constituent in ACI exhaust PM

- Mass
- Merit
- Cold-start dry-soot data supports update of -H(X) function
  - From 2.0 to 1.6
- Total PM carbon (EC +OC) shows greater PM mass but trend follows PMI

Any proposed future work is subject to change based on funding levels

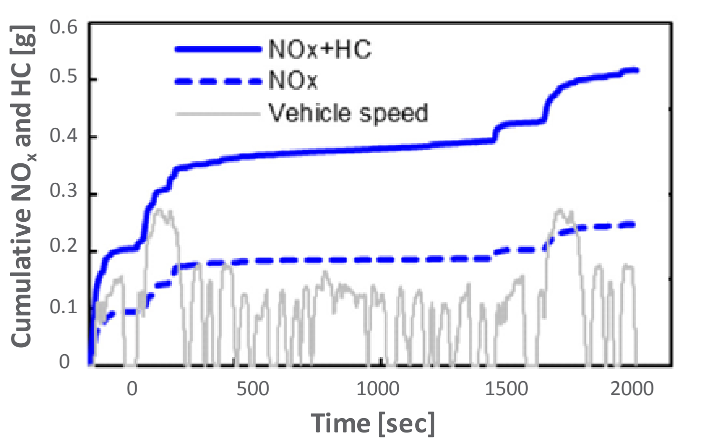
Project Summary #5

Oak Ridge National Laboratory

Fuel Impacts on Emissions Control Performance & Durability ($175K)

Todd Toops and Josh Pihl (co-PIs)

William Brookshear and Sreshtha Majumdar

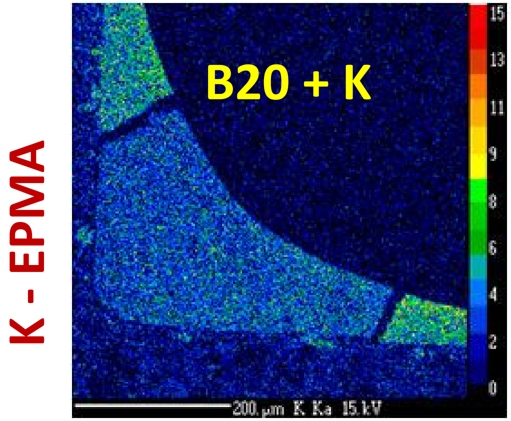


Murata, Y., Morita, T., Wada, K., Ohno, H., SAE Int. J. Fuels Lubr. 8 (2015) 454.

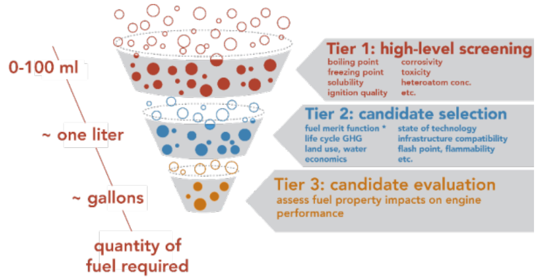
Relevance and Approach

- Objective: Understand the effects of Co-Optima blendstock candidates on emissions control devices

Evaluate effects of trace impurities in Co-Optima blendstock candidates

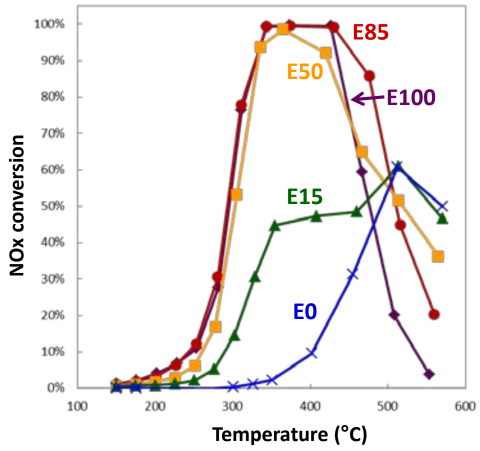


Develop screening criteria and merit function terms related to gaseous emissions



$$Merit = \frac{(RON_{mix}-91)}{1.6} - K\frac{(S_{mix}-8)}{1.6} + \frac{0.085[ON/kJ/kg_{mix}]\cdot((HoV_{fuel}/(AFR_{stoich}+1)) - (415[kJ/kg_{fuel}]/(14.3[-]+1)))}{1.6}$$
$$+ \frac{((HoV_{fuel}/(AFR_{stoich}+1)) - (415[kJ/kg_{fuel}]/(14.3[-]+1)))}{15.38} + \frac{(S_{L\,mix} - 46[cm/s])}{5.4}$$
$$- H(PMI-1.6)[0.7+0.5(PMI-1.4)] + 0.008\,°C^{-1}(T_{c,90,conv} - T_{c,90,mix})$$

Identify opportunities to reduce emissions and fuel penalty through co-optimization



Outcome: Identification of criteria pollutant emissions control challenges and opportunities created by Co-Optima blendstock candidates

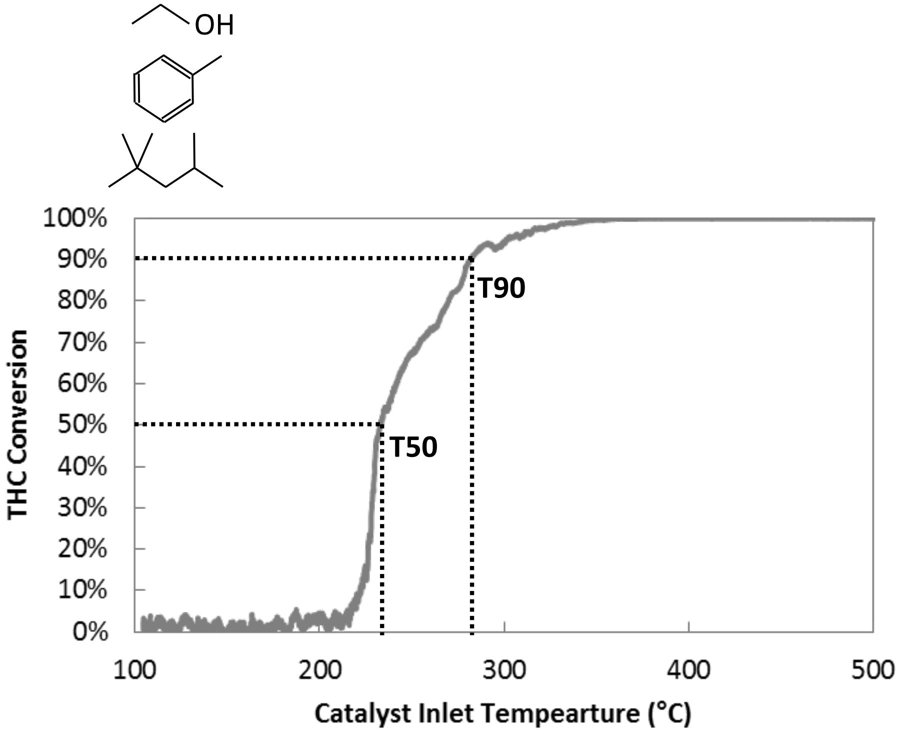
Measuring TWC light-off temperatures of blendstocks for evaluation of Merit Function emissions control term

Technical Accomplishments

- Developed Merit Function Emissions Control term based on cold start fuel penalty (see backup slides for details)

$$0.008\ °C^{-1}\left(T_{c,90,conv} - T_{c,90,CB}\right)$$

- Measuring catalytic light-off temperatures ($T_{c,90}$) of Co-Optima SI-intended blendstocks
  - aged commercial TWC
  - synthetic exhaust flow reactor
  - ***blendstocks T_{90} ≤ E10 T_{90}***



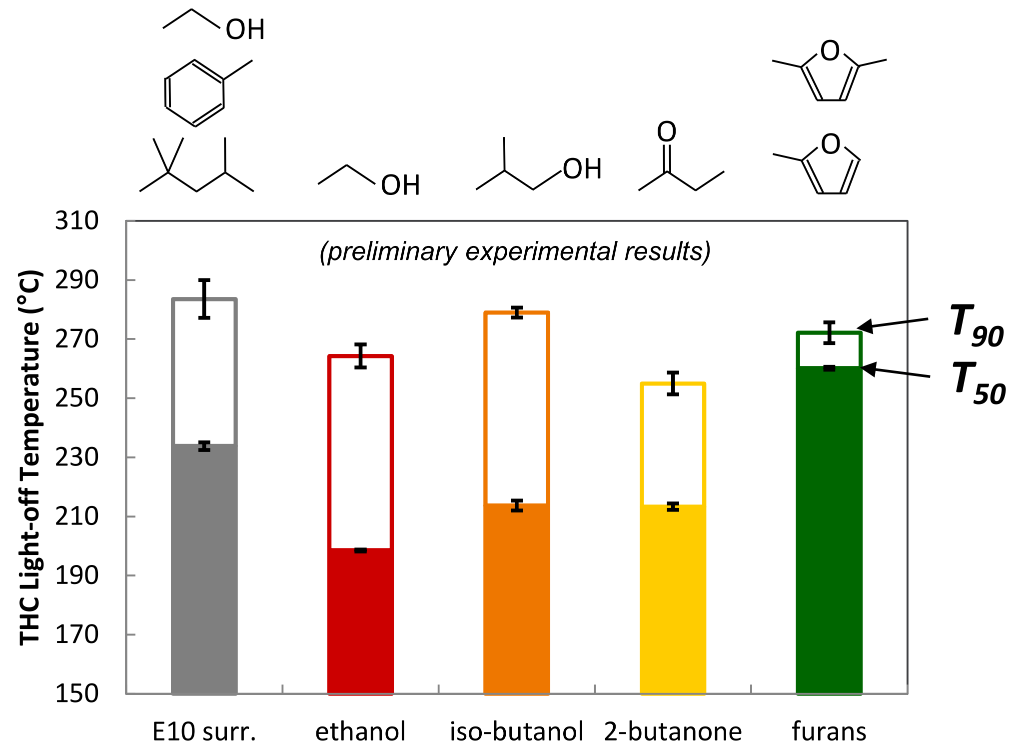
Measuring TWC light-off temperatures of blendstocks for evaluation of Merit Function emissions control term

Technical Accomplishments

- Developed Merit Function Emissions Control term based on cold start fuel penalty (see backup slides for details)

$$0.008\,{}^\circ C^{-1}\left(T_{c,90,conv} - T_{c,90,CB}\right)$$

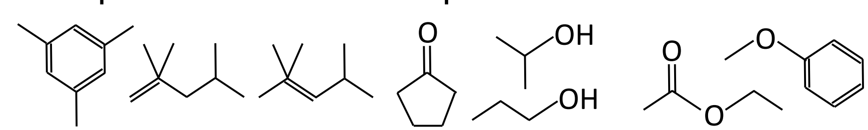
- Measuring catalytic light-off temperatures ($T_{c,90}$) of Co-Optima SI-intended blendstocks
  - aged commercial TWC
  - synthetic exhaust flow reactor
  - ***blendstocks T_{90} ≤ E10 T_{90}***



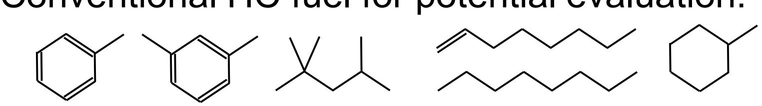
Future Work

- FY18 plans: measure light-off temperatures for selected blends
  - develop correlation to predict blend light-off based on pure components

Co-Optima candidates for potential evaluation:

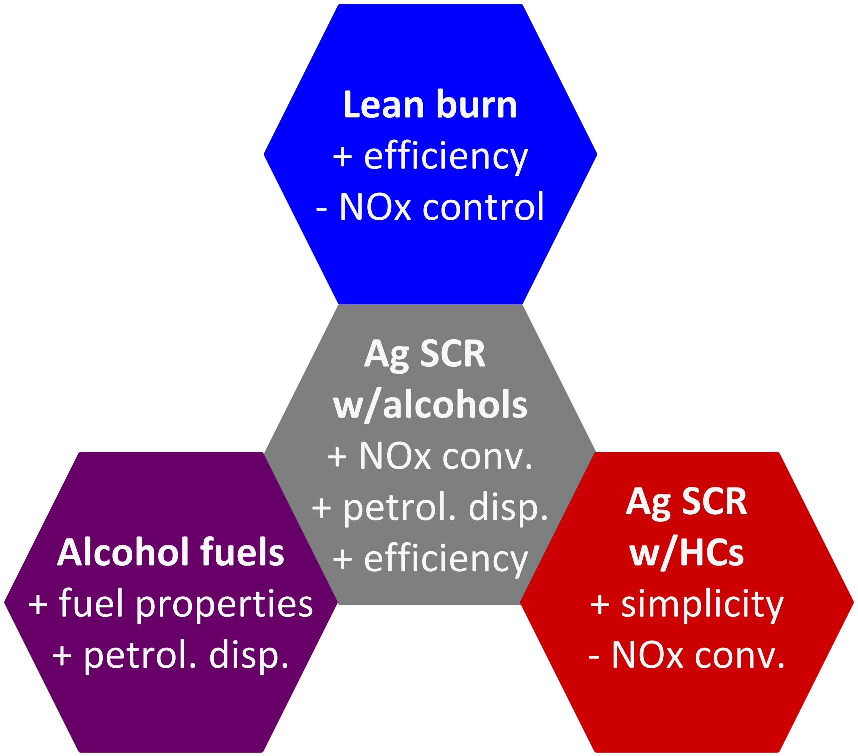


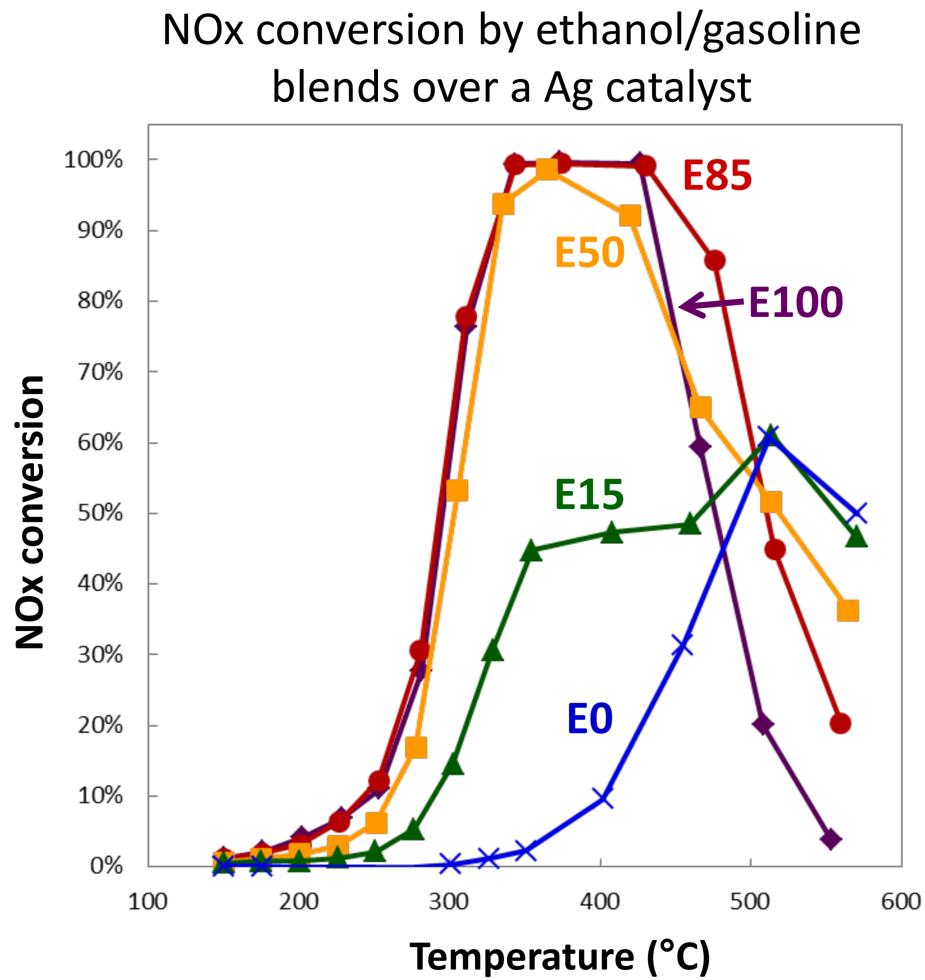
Conventional HC fuel for potential evaluation:



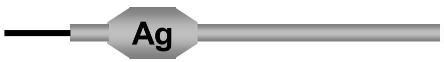
Any proposed future work is subject to change based on funding levels

NO SCR by alcohol-containing fuels could be a pathway to NOx control for SI/ACI lean burn engines



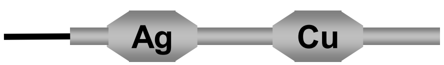


Dual SCR approach improves emissions control performance over a Ag-only system with E85 reductant



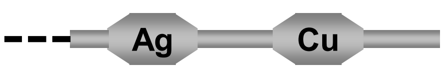
(Ag only, steady fuel)

- achieves high NOx conversion efficiencies over a limited T window
- results in higher than acceptable fuel penalty, NH_3 yield, HC slip



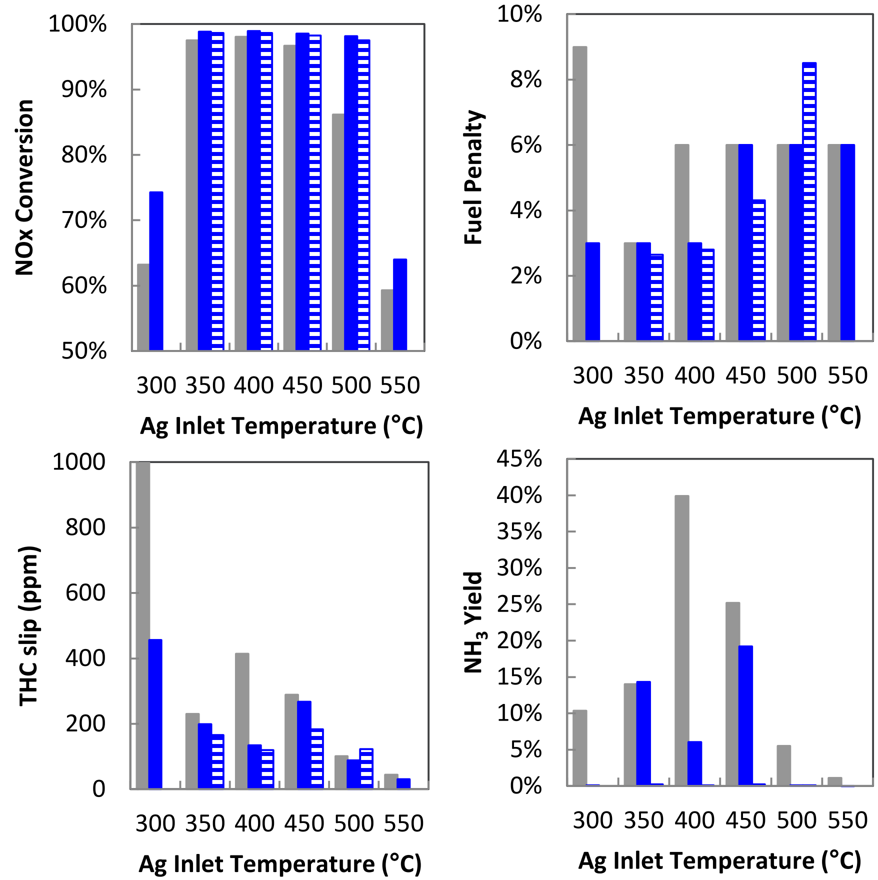
(Ag+Cu, steady fuel)

- improves NOx conversion efficiencies
- reduces fuel penalty, NH_3 slip, HC slip



(Ag+Cu, fuel pulses)

- maintains high NOx conversion efficiencies
- reduces fuel penalty and HC slip
- eliminates NH_3 slip



Experiments conducted with Ag/Al_2O_3 and Cu-SSZ-13 catalysts on a synthetic exhaust gas flow reactor using 15% ethanol + 85% cert. gasoline

Dual SCR approach improves emissions control performance over a Ag-only system with E85 reductant

Ag (Ag only, steady fuel)

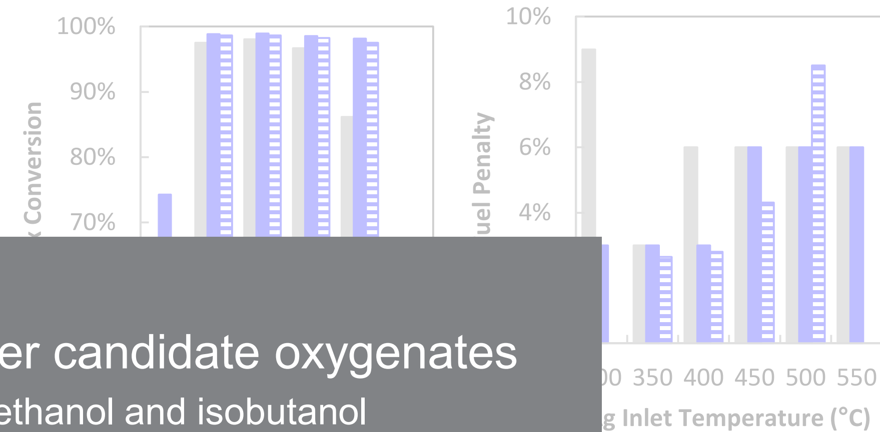
- achieves high NOx conversion efficiencies over a limited T window
- results in penalty, N

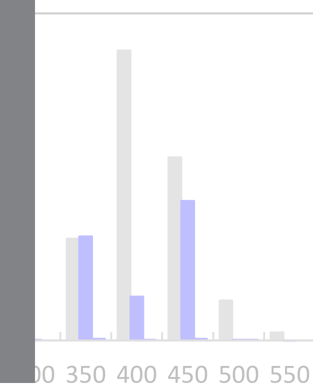
Ag

- improves
- reduces fu

Ag

- maintains efficiencies
- reduces fuel penalty and HC slip
- eliminates NH_3 slip



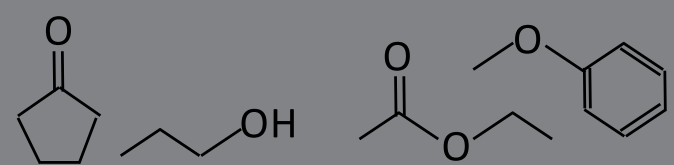


Ag Inlet Temperature (°C)

Experiments conducted with Ag/Al_2O_3 and Cu-SSZ-13 catalysts on a synthetic exhaust gas flow reactor using 15% ethanol + 85% cert. gasoline

Future Work/directions

- Evaluate reactivity of other candidate oxygenates
  - Have already evaluated ethanol and isobutanol



- Efforts are ongoing to acquire newer catalyst technology from Umicore

Any proposed future work is subject to change based on funding levels

Collaboration

- **Co-Optimization of Fuels and Engines** brings together expertise from across the National Laboratory system, working toward a common purpose. This effort has stakeholder engagement at a high level to ensure relevance.
  - 9 laboratories, engines, fuels, kinetics, simulation, biofuel development, LCA& TEA, market transformation
  - Monthly stakeholder engagement phone calls, industry listening days, external advisory board
- Projects presented at the semi-annual AEC program review meetings
- Engagement with ACEC Tech Team activities

Additional project-level collaborations with industry and academia:

- **NREL: Particulate Matter Index (PMI) refinement**
  - Colorado State University
- **ORNL: Fuel Impacts on Emissions Control Performance & Durability**
  - University of Michigan - Galen Fisher
  - Emissions Solutions (currently CDTi – Clean Diesel Technologies, Inc.)

Response to last year's AMR scores

- **Approach:** **getting an early look at the engine out emissions would help downselect candidate fuels and regimes**…spray work feeding into the modeling team is a critical effort that should be continued…emissions work looking at fuel impurities is critical to get an early look at impact of biofuels
- **Technical Accomplishments:** technical accomplishments to date are impressive … projects on the spray and emission control research were much better … **it is not clear how the planned emissions activities will address emissions control for LTC or ACI engine concepts**
- **Collaborations:** collaborative work between the labs is impressive … **collaborations with external stakeholders and companies is either not presented or at a low level**
- **Future plans:** spray and emissions research outlined for future work is very relevant … **proposed projects and work is scattered with no clear plan to determine winners and losers**
- **Relevance:** the emissions research is expected to contribute to achieving improved engine efficiency along with lower emissions … **it is not clear that the Thrust II technologies will prove to be more fuel efficient and displace petroleum**
- **Resources:** **the project needs resources to look at toxics and other unintended consequences … Thrust II does not have a clear focus and seems a bit excessive, especially given that this technology is more than 15 years away and not the current focus of OEMs**

Responsive Actions
1. When Thrust II/ACI engine research ramps up emissions measurements will absolutely be a significant part of the effort
1. Lean gasoline approach currently being investigated is focused on a Thrust I/Thrust II (SI/ACI) multimode operation; more thrust II ramping up next FY; researchers have low temperature catalyst projects to draw from
1. Engagement is primarily through the advisory board and stakeholders group of Co-optima
1. Co-optima not organized to pick winners and loser, but to provide relevant data for industry to make decisions in a coordinated fashion
1. Lean operation generally has the potential to be more efficient, but fully understanding all sides of the efficiency questions is a goal of program
1. Additional funding always appreciated, but funding levels expected to be flat *2. Important considerations being discussed at the leadership level*

Summary

Relevance

- Understanding fuel effects on spray structure and on aftertreatment devices is central to the co-optimization of fuels and engines
- Determining fuel impact on PM is critical for predicting or avoiding PF for 2025 PM Regulations
- Understanding fuel impact on emissions and emissions control critical for meeting regulations, avoiding deactivating impurities and understanding potential opportunistic chemical behavior

Approach

- Individual projects are coordinated to a high degree and seek to build on the strengths of the labs

Accomplishments

- Establishing spray capabilities for flammable co-optima fuels at two national laboratories
- Evaluation of PMI for oxygenated fuels through factorial design and cold-start evaluation
- Assessing impact of fuels TWC light off behavior of pure compounds under consideration for SI
- Highlighting synergistic behavior of ethanol and silver and copper catalysts for dual SCR of NOx

Collaborations

- "Co-Optima" has 9 National Labs, stakeholder engagement, and external advisory board
- Projects presented at AEC semi-annual program review, engaged with ACEC TT, SAE World Congress and Co-Optima All-Hands Meeting

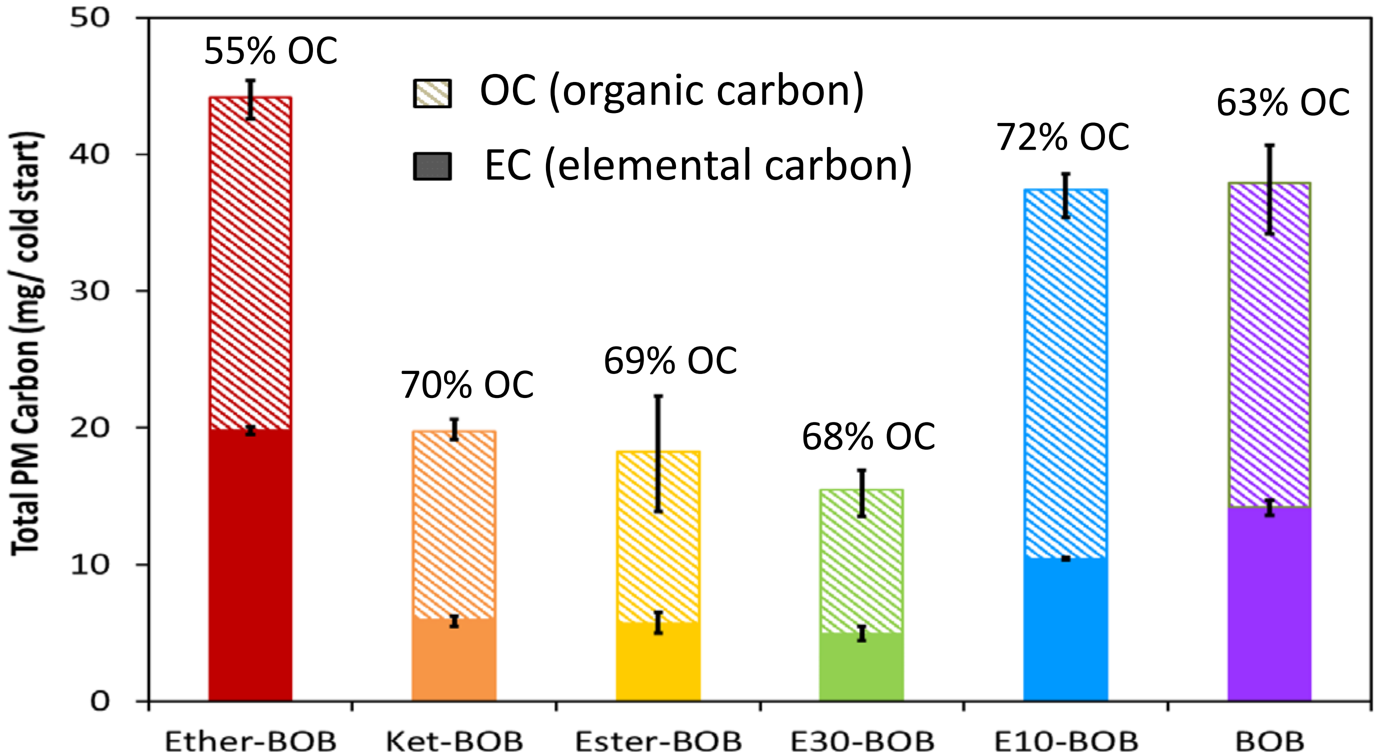
Future Work

- Spray research will start evaluating Co-Optima fuels very soon
- PMI factorial experimentation will be completed and adjustments to the PMI term will be evaluated
- Complete analysis of cold-start collected PM and identify pathway to PM formation based on fuel
- Complete TWC light-off evaluation of Co-optima SI-fuels and evaluate other oxygenates in dual SCR technique

Any proposed future work is subject to change based on funding levels

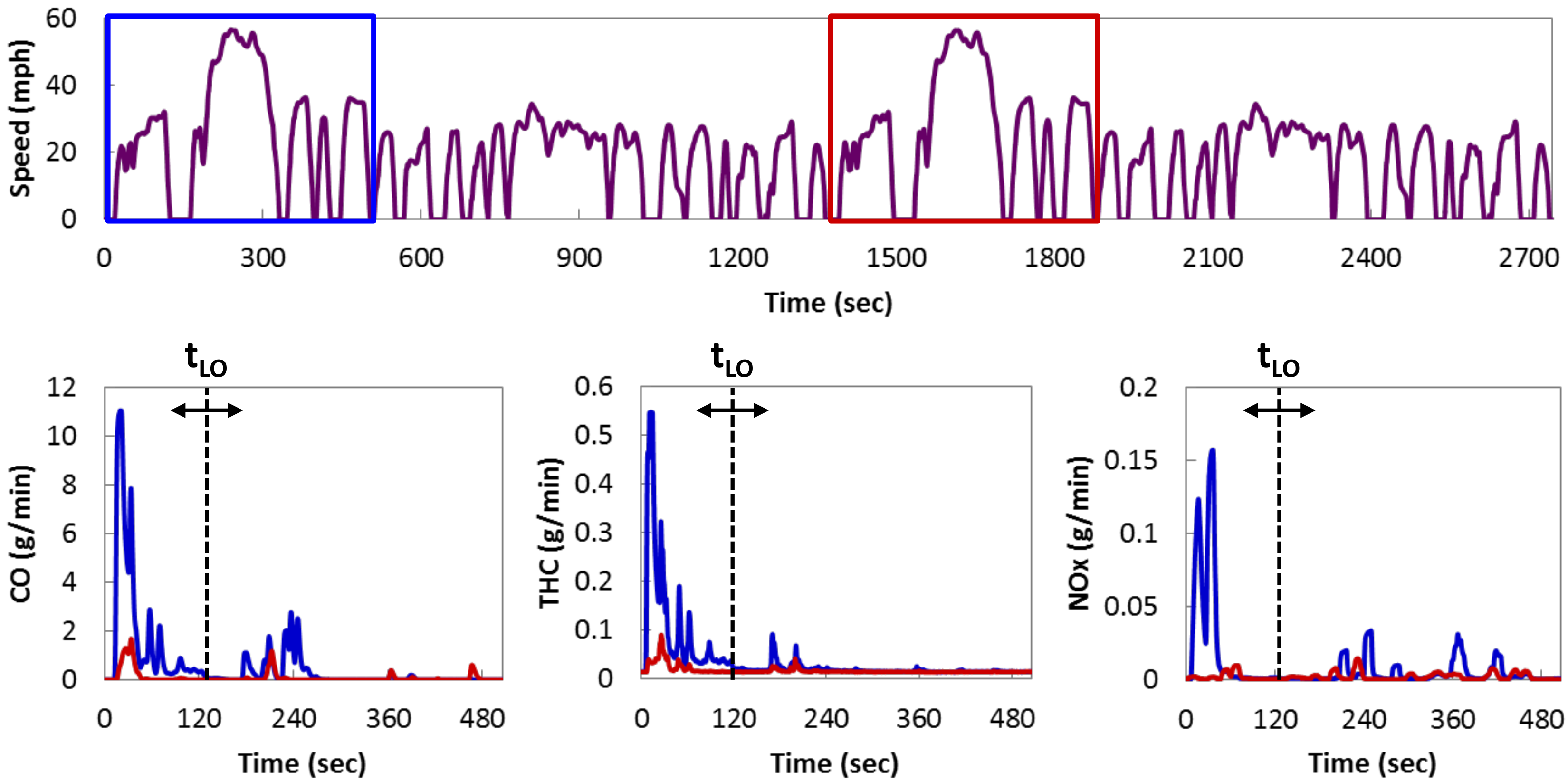
TECHNICAL BACK-UP SLIDES

Organic Carbon dominates Cold-Start PM



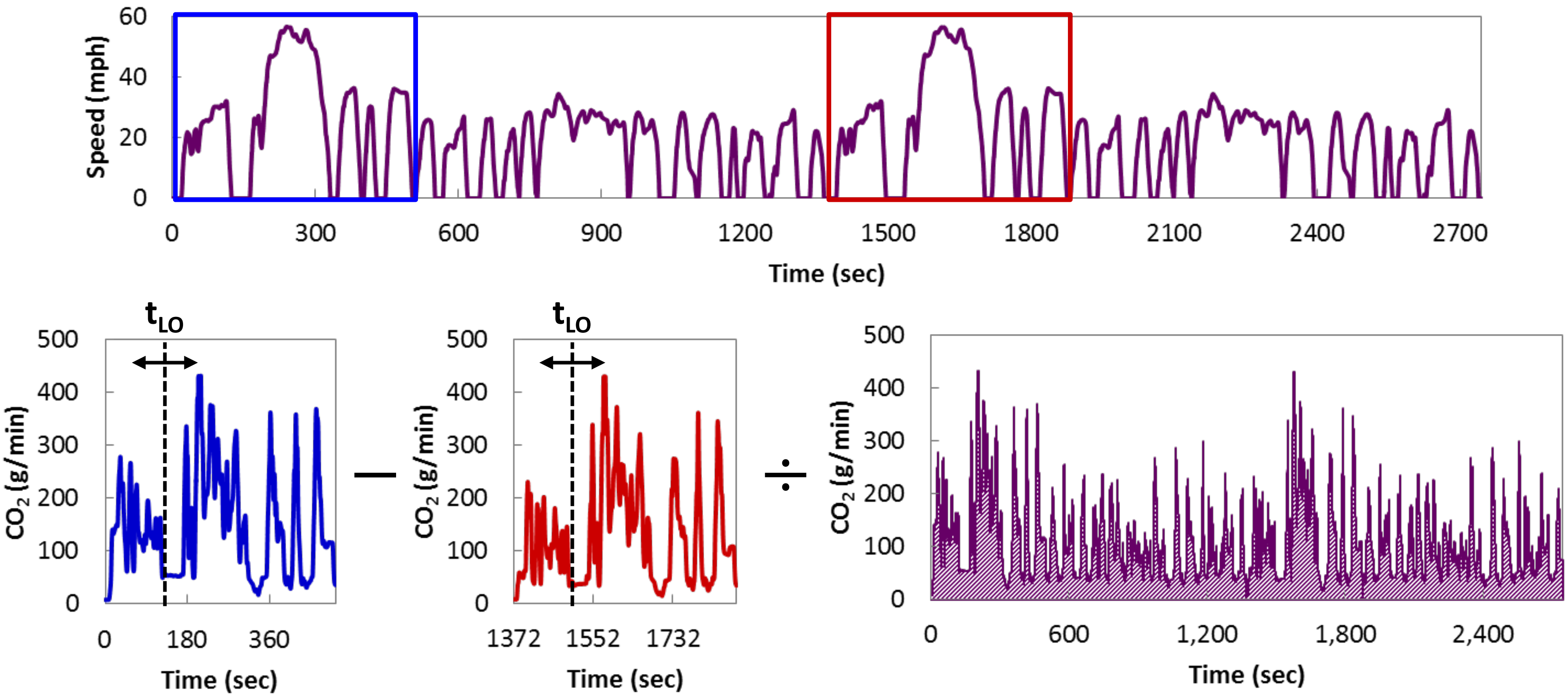
- Gravimetric quartz filter sampling
  - NIOSH 450 method for ec/oc analysis
  - Triplicate filters (6 cold-starts per filter)
- Greater than 50% of PM is considered OC for all fuels

Development of a SI Merit Function Emissions Control Term Based on FTP Cold Start Fuel Penalty



- Need method to correlate emissions performance with fuel efficiency for inclusion in SI merit function
- Most emissions for stoichiometric SI engines released during cold start
- Extra fuel burned during cold start to heat catalyst decreases efficiency

Development of a SI Merit Function Emissions Control Term Based on FTP Cold Start Fuel Penalty



- Cold start fuel penalty = (hot start CO_2 - cold start CO_2) ÷ total FTP CO_2
- Cold start fuel penalty proportional to catalyst light-off time, which depends on light-off temperature, which will vary with fuel composition

$$\frac{\Delta F_{LO,conv} - \Delta F_{LO,CB}}{F_{FTP}} \approx \frac{\Delta f_{LO}}{F_{FTP}}\left(t_{LO,conv} - t_{LO,CB}\right) \approx \frac{\Delta f_{LO}}{F_{FTP}}\alpha\left(T_{c,90,conv} - T_{c,90,CB}\right) \approx \boxed{0.008\ ^{\circ}C^{-1}\left(T_{c,90,conv} - T_{c,90,CB}\right)}$$

Cold-Start FTP Equivalent Calculation

$$\left[\frac{m' + m''}{D' + D''} * 0.43\right] + \left[\frac{m''' + m''}{D' + D''} * 0.57\right] = Y$$

$$\left[\frac{m' + m''}{D' + D''} * 0.43\right] = \left[\frac{X'}{7.47} * 0.43\right] + \left[\frac{X}{7.47} * 0.43\right]$$

$$X' + X = m'$$

$$D' + D'' = 7.47\ miles$$

Therefore, $\frac{X'(mg)}{7.47\ (miles)} * 0.43 = Y'\ (mg/mile)$

X' = PM per (90s) cold-start transient (mg)
Y' = Cold-start PM FTP equivalent (mg/mile)
Y = Total FTP PM rate (mg/mile)
X = mass of PM from FTP Bag 1 after 90s transient

m′ = mass of PM from FTP Bag 1
m″ = mass of PM from FTP Bag 2 and 4
m‴ = mass of PM from FTP Bag 3
D′ = FTP miles for Bag 1 and 3
D″ = FTP miles for Bag 2 and 4